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ABSTRACT

Physics learning studies demonstrate that students' pre-instructional world knowledge is often logically antagonistic to the principles of Newtonian mechanics taught in introductory physics courses. Under these conditions psychological theory predicts that learning will be inhibited, a prediction consistent with both the experiences of physics teachers and the results of empirical investigation. Informed by cognitive research on problem solving, semantic memory, and knowledge acquisition, instruction has been designed to encourage the reconciliation of world knowledge and physics content among beginning physics students. These instructional objectives and strategies for mechanics instruction are derived from the analysis of the cognitive states of uninstructed students, novices, and experts, groups who differ with respect to: (1) the quantity and extent of formal mechanics instruction; (2) experiences in solving mechanics problems; and (3) the extent of their verbal interactions about mechanics. Illustrative procedures which employ the strategies (also useful for other subject-matter domains) are included. (Author/JN)

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COGNITIVE RESEARCH AND THE DESIGN OF SCIENCE INSTRUCTION

1983/13

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Cognitive Research and the Design of Science Instruction

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The utilization of cognitive psychological theory and findings from research to inform the design of instruction is illustrated in this paper. Physics learning studies demonstrate that students' pre-instructional world knowledge is often logically antagonistic to the principles of Newtonian mechanics taught in introductory physics. Under these conditions psychological theory predicts that learning will be inhibited, a prediction consistent with both the experiences of physics teachers and the results of empirical investigation. Informed by cognitive research on problem solving, semantic memory, and knowledge acquisition, instruction has been designed to encourage the reconciliation of world knowledge and physics content among beginning physics students.

> Most science textbooks can be criticized by drawing attention to the fact. . . . that these books are chiefly concerned with the statements of results. Usually the most general results are put near the beginning of the textbook. A textbook in physics begins by telling about molecules and the constitution of matter or by giving some of the most compactly formulated statements about the principles of mechanics . . . . The degree of enthusiasm of the ordinary student for these introductions which he gets in the textbooks is very slight indeed . . . . The student, confronted by these verbal additions to his experience, gets into the habit of thinking of science as verbal additions to experience, and he faithfully learns the words and keeps them in store against the time when the teacher demands them. (Judd, 1915, pp. 334-336)

Introduction

One recent trend in cognitive psychology has increasingly focused the attention of researchers on learning tasks representative of those which students encounter in school instruction (Greeno, 1980). Developments such as this hold the promise of an improved theoretical basis for instruction. A theoretically organized and systematically verified psychological foundation is an essential requisite for effecting substantial improvements in instruction. However, the existence of such theory offers no guarantee that instruction systematically and veridically incorporating principles derived from the theory will be designed. A necessary condition for the systematic application of theory to instructional practice is a science of design as ". . . a body of intellectually tough, analytic, partly formalizable, partly empirical, technical doctrine about the design process (Simon, 1981, p. 132)." Only when a science of instructional design exists will the design process cease to hide behind the cloak of "judgment" or "experience."

This article is motivated by the need to make explicit the design process as it applies to the design of instruction, explicit description of the process being a necessary first step in the development of a science of instructional design. We describe how we have applied the theory and empirical findings of cognitive psychology to devise a course of action aimed at changing an existing situation into a desired one (Simon, 1981, p. 129). Specifically, the course of action is the instruction, the existing situation is the cognitive state of the uninstructed student, and the desired situation is a student's cognitive state that approximates specified features characteristic of the cognitive state of an expert in the field (the ideal state).

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The design process to be explicated in this article represents an alternative approach to the design of instruction. Central to this process is the analysis of customary instructional tasks for the purpose of specifying the underlying cognitive processes and structures that are necessary for the successful completion of the task. The specification of these processes and structures for a variety of school subject-matter domains represents an important part of the recent empirical findings of cognitive science research. Thus, if detailed process and structure descriptions appear to be helpful in designing instruction in physics (as we intend to demonstrate), they should also be helpful in designing instruction in other domains.

We begin by describing the practical relevance of the instructional problem that interests us, namely, student difficulties in the learning of classical Newtonian mechanics.

The Instructional Problem

There is a general agreement among physics instructors and students that mechanics is difficult to teach and to learn (Kolody, 1977). Students have difficulty comprehending classical mechanics, and physics instructors often express disappointment with the outcome of their efforts to instruct students in classical mechanics. This instructional problem has been discussed at length in the literature of physics education where various underlying causal factors contributing to the problem have been suggested (Gerson & Primrose, 1977; Halley & Eaton, 1974; Hudson & McIntire, 1977). Two distinct perspectives on this learning problem are identifiable.

One perspective assumes that learning difficulties occur when the learner is deficient in skills which are assumed to be prerequisite to the study of physics (e.g., Arons, 1976; Renner, Grant, & Sutherland, 1978). The other perspective links the observed learning difficulties with the fact that students coming to introductory physics courses have firmly embedded conceptualizations of how and why objects move, and that these conceptualizations are in clear conflict with the canonical view of that subject-matter domain which the student will be required to learn. One line of science education research and psychological research on semantic memory is particularly relevant to the second perspective.

Research Background

Pre-instructional Knowledge and Students' Interpretation of Instruction

The research we examine furnishes a context for describing the existing situation, the uninstructed student's cognitive state, and distinguishing it from the desired situation. Various empirical studies conducted by science educators (including Brumby, in press; Driver, 1973; Driver & Easley, 1978; Fleshner, 1963; Gunstone & White, 1981; Leboutet-Barrell, 1976; Rowell & Dawson, 1977; Singer & Benassi, 1981; Viennot, 1979) and psychologists (including Clement, 1979; Green, McCloskey & Caramazza, 1980; Selman, Jaquette, Krupa, & Stone, in press) demonstrate that, for several science content areas:

1. Students have descriptive and explanatory systems for scientific phenomena that develop before they experience formal study of the subject.

2. These descriptive and explanatory systems differ in significant ways from those the students are expected to learn as the result of formal study.

3. These alternative conceptual systems show remarkable consistency across diverse populations.

4. These alternative conceptual systems are remarkably resistant to change by exposure to traditional instructional methods.

5. These alternative conceptual systems are not facilitative to the learning process. Students interpret instructional events (for example, experiments and expository text) in the context of the conceptual scheme they currently hold, not the one that the experiments or the text are designed to convey.

These effects are particularly striking in the context of mechanics where prior to formal instruction young people and adults have a conception of motion that is more

Aristotelian[1] than Newtonian (Champagne, Klopfer, Solomon, & Cahn, 1980; Clement, 1979; Driver, 1973; Driver & Easley, 1978; Lebouteé- Barrell, 1976; Singer & Benassi, 1981; Viennot, 1980). Other research findings show that remnants of the Aristotelian conception persist with many "successful" physics students, that is, with students receiving high grades in introductory physics courses (Champagne, Klopfer & Anderson, 1980; Gunstone & White, 1981). This research provides empirical support for what physics teachers have long observed, namely, that traditional instruction does not facilitate an appropriate reconciliation of preinstructional knowledge with the content of instruction. (Ausubel, Novak, & Hanesian, 1978).

A study by Lebouteé-Barrell (1976) indicates that high school and college students have misconceptions about force and motion which persist despite instruction. The misconceptions are described as pre-Galilean. In a study by Cole and Raven (1969) with 12 to 15 year-olds, it was necessary to give the students "opportunities to reject irrelevant factors in understanding the principle of flotation." Rowell and Dawson (1977) also explicitly considered common misconceptions when designing instruction on the law of floating. Despite efforts to refute misconceptions in instruction, some misconceptions persisted. Instructional work by Fleshner (1963) in the Soviet Union indicates that students' intuitive ideas may coexist with ideas derived from instruction. In a study by Driver (1973), 1' and 12 year-old students were interviewed prior to, during, and after instruction on several topics of a physical science course. Although alternative theoretical frameworks to explain observations were introduced to the students and used during the instruction, Driver reports that counter-examples and conflicting evidence did not produce changes in students' thinking.

Our own work (Champagne, Klopfer, & Anderson, 1980; Champagne, Klopfer, Solomon, & Cahn, 1980) has demonstrated that prior knowledge affects students' comprehension of science instruction. We have been particularly interested in the difficulty that beginning physics students have in learning classical mechanics. Our research has demonstrated that it is not the students' lack of prior knowledge which makes the learning of this topic so difficult, rather their conflicting knowledge. They come to instruction with well-formed notions about the motion of objects — notions that have been reinforced by their experiences. However, their notions may stand in contradiction to the tenets of classical physics, and these notions tend to interfere with or inhibit the learning of mechanics. This research demonstrates specific ways in which students' conceptions influence (a) their understanding of science texts and lectures, (b) their observations, and (c) their interpretations of their observations. Often the influence of the students' conceptions is to inhibit their understanding or distort their observations and interpretations of experiments.

Other research (Champagne, Klopfer, & Anderson, 1980) demonstrates that the belief in the proposition, heavier objects fall faster than lighter objects, is not readily changed by instruction, thus demonstrating the strong influence that prior knowledge has on the effectiveness of instruction — in this case the prior knowledge having an inhibiting effect on learning. In a study of beginning college physics students, about four students in five believed that, all other things being equal, heavier objects fall faster than lighter ones. These results were particularly surprising since about 70% of the students in the sample had studied high school physics, some for two years. A chi-square test showed that students in the sample who had studied high school physics did not score significantly better than those who had not. This finding has been replicated in follow-up studies.

In a report of a similar study of the knowledge of gravity possessed by beginning first-year physics students at Monash University, all of whom had successfully completed two years of high school physics, Gunstone & White (1981) conclude: (a) ". . . students know a lot of physics but do not relate it to the everyday world;" and (b) "In many instances the students used mathematical equations to

[1] Aristotle considered rest to be the natural state of objects. In the absence of any cause, an object does not move; conversely, when an object is moving, it must have been caused, usually by a force. Aristotle also argued that the *speed* of an object is directly proportional to the force acting on it, and inversely proportional to the resistance of the medium through which the object is moving. In the Newtonian physics of today, it is stated that an object will continue in its existing state (either at rest or moving with constant speed in a straight line) unless it is acted on by a *net* force. The *acceleration* of the object is directly proportional to this net force and inversely proportional to the mass of the object.

explain predictions, though often inappropriately, which indicates that they had lots of physics knowledge to hand [*sic*] but were unskilled in seeing which bit applied to the given situation (p. 299)." In their conclusions, Gunstone and White note that " . . . much more attention may have to be given to integrating the knowledge acquired in school to general knowledge (p. 298)."

The difficulty is compounded by the fact that many of the terms used in classical mechanics are also used in everyday life — terms such as acceleration, momentum, speed, and force. The meanings of these terms as used by physicists are quite different from the way in which they are used in everyday life. Thus, we observe that students misinterpret mechanics instruction because they interpret physics lectures and textbooks in the context of their everyday understanding of the terms rather than in the way in which the teacher or text is using the terms.

Theoretical analysis. These descriptions of the interactive effects of knowledge on understanding are consistent with findings emerging from cognitive psychology that demonstrates the impact of existing knowledge in memory on the comprehension of text (Anderson, Reynolds, Schallert, & Goetz, 1977; Bransford & McCarrell, 1974; Lindsay & Norman, 1972). This research demonstrates that all incoming stimuli which are remembered are subject to reorganization by the learner. The incoming stimuli are primarily restructured by the learner in terms of the learner's own past experiences, and only secondarily in terms of the organizing principles of the material itself. In instructional situations generally, students engage in active, *meaningful* structuring of text they read and lectures they hear in order to remember and understand incoming information.

Cognitive psychologists have studied ways in which prior semantic knowledge influences comprehension of verbal materials. The early studies in the area of reading comprehension aimed at demonstrating that something other than the linguistic structure of a sentence is required to explain a person's comprehension of that sentence. The "something other" is described as the person's world knowledge and is often characterized as a "schema," "plan," or "script." Bransford and McCarrell (1974) review studies which indicate that the process of understanding text involves creation of "semantic descriptions" that use both the reader's world knowledge and the sentence input. In this research, the contexts for interpretation of text either were common world knowledge or were induced by the experimenter. Anderson et al. (1977) indicate that an individual's "private" representation of the world can affect text comprehension. In general, studies of text comprehension indicate the facilitative effect of schemata or world knowledge. However, studies of physics learning indicate that world knowledge is logically antagonistic to the content to be learned and often persists after physics instruction.

Cognitive Contents of Uninstructured Physics Students' Cognitive State.

From our analysis of empirical studies investigating students' preinstructional conceptions of the motion of objects, we conclude that the following are characteristic of the contents of the cognitive state of uninstructed physics students:

1. Concepts are poorly differentiated. For example, students use the terms speed, velocity, and acceleration interchangeably; thus, the typical student does not perceive any difference between two propositions such as these — (a) the speed of an object is proportional to the [net] force on the object; (b) The acceleration of an object is proportional to the [net] force on the object.
2. Meanings physicists attribute to terms are different from the everyday meanings attributed to the terms.
3. Propositions are imprecise and the imprecision derives from several different sources.
   (a) Some of the imprecision of propositions is attributable to the meanings students have for technical concepts which are different from the canonical meaning. Example: More force means more speed.
   (b) Other imprecision can be interpreted as errors of scale (Gunstone & White, 1981). Example: Gravity pulls harder on objects that are closer to the earth. (This proposition, in the context of an object falling a distance of three meters, is correct only in theory because the difference in the force of gravity (approximately 1 part in 10^{13}) is too small to measure.

If, however, the difference in distance from the earth were large (several hundred kilometers), the difference in the force of gravity is significant.)
(c) Other propositions are just wrong and may arise because of students' attempts to inappropriately formulate general rules of motion from their experiences in the real world. Example: Heavy objects fall faster than lighter objects.

Implications for instruction. Research reviewed in this section demonstrates that the cognitive contents of the uninstructed student differs from the desired state with respect to propositions and the meaning of concepts. Uninstructed students apply propositions that link force with motion, whereas Newtonian mechanics links force with *change* in motion. Moreover, the meaning uninstructed students attribute to technical terminology is different from the technical meaning. For example, the technical meaning of acceleration is a change in the magnitude of velocity or direction of velocity of an object, while the meaning uninstructed students attribute to acceleration is speeding up.

Application of the Simon paradigm to the design process requires detailed specification of the meaning concepts have for the uninstructed person and the principles that uninstructed persons apply in the analysis of motion. Such specifications are prerequisite to the process of specifying the goals of instruction, and they allow for (a) the generation of hypotheses about why certain instructional practices are not successful, and (b) the construction of possible mechanisms that will result in the desired changes in the learners' cognitive state.

Differences like those described above between the uninstructed learners' cognitive state and the desired cognitive state provide clear specifications of changes instruction should produce. The instructional goal, then, is to bring about the specified changes in the learners' cognitive state. We hypothesize that the observed differences between the uninstructed and desired cognitive states result in certain of the difficulties that students experience in learning mechanics, an interpretation that is consistent with cognitive theory. We further hypothesize that the observed interactive effects of prior knowledge and instruction may be more pronounced for mechanics than for other subjects.

The development of practical principles of motion is necessary for coping with the moving objects that are encountered in daily life. Thus, all students begin the formal study of mechanics with an experientially verified set of principles that allow them to predict the motion of objects under the conditions prevalent in the real world. In addition, the same words that are used to describe and explain motion in everyday language also are used by physicists.

Contrast this situation with thermodynamics or chemistry where the words used for technical concepts are not a part of everyday language (mole, enthalpy, entropy) and where principles need not be developed to cope with frequently encountered situations. In these and similar subject areas, traditional expository instruction is more successful. However, in mechanics, instructional strategies need to be applied that can make students aware of differences between their everyday meanings of words and principles of motion and those of the instruction.

Before presenting detailed hypotheses related to strategies which will produce the desired changes in the cognitive contents of uninstructed students, other relevant characteristics of the learners' cognitive state will be described.

Structural and Representational Features of Physics Knowledge and Physics Problem Solving Strategies

The preceding analysis focused on the contents of memory — propositions and meaning of concepts — and hypothesized how students interpretation of instruction — understanding of lectures, text and experiments — is influenced by significant differences between the subject matter to be learned and the students' cognitive contents. This section focuses on the organization of the contents of memory: its structural features and modes of representation; the differences between the structural organization and representations of expert physicists, novices and uninstructed physics students; and the implications of these differences for physics instruction.

Descriptions of the structural features and representations of physics knowledge derive principally from research on physics problem solving. Researchers in the domain of problem solving are concerned with both the strategies and structures that problem solvers are

observed to apply in the successful solution of problems (e.g., Greeno, 1978; Newell & Simon, 1972). We shall review, in turn, the pertinent research findings on structural organization and problem solving strategies.

Structural organization and representation. Research on physics problem solving provides descriptions of the structural organizations and representations characteristic of expert and novice problem solvers. The solution of physics problems requires both the availability of problem solving strategies and the understanding of physical situations which are observed directly or described in the text of the problem. Current theories of semantic memory and natural language understanding (Anderson, 1976; Anderson et al., 1977; Bransford & McCarrell, 1975; Kintsch, 1974; Lindsay & Norman, 1972; Norman & Rumelhart, 1975; Quillian, 1968; Schank, 1972; Winograd, 1972) tie the existence of relevant schemata to the process of making inferences and coming to understand a situation.

In the context of physics, understanding implies (a) the construction of mental representations of physical situations that include the objects that are a part of the physical situation, (b) the concepts and scientific principles that are relevant to the situation, and (c) the relationships that exist between objects, concepts and principles (Winograd, 1972). Essential to the construction of a mental representation is the process of inference. Making valid inferences is dependent on schemata that are relevant, correct and complete. Thus, understanding physical situations as physicists understand them requires both that the relevant schema is present and that the features of the physical situation evoke the schema.

Recent work by Chi, Feltovich, and Glaser (1981) describes the following explicit differences in schemata of experts and novices: (a) The schemata of experts are based on physical principles (for example, energy conservation and Newton's Second Law), but the schemata of novices are based on physical objects (for example, springs and inclined planes) and mental constructs (for example, friction and gravity). (b) The contents of the schemata of experts and novices do not differ significantly in information content; however, the novices' structures lack important relations, specifically relations between the surface features of the problem and the scientific principles which are the basis for solutions. (c) Experts translate surface features of the problems into canonical objects, states, and constructs, while the novices represent the problem in terms of the literal objects and constructs described in the text of the problem. (d) Links exist in the experts' representations of knowledge structures between the abstract representation of features of the problems and the physical principles which are the basis for the solution of the problem. (e) Experts' schema are organized hierarchically along the dimension of abstractness; in contrast, the different levels of the novices' knowledge are not well integrated, thus preventing easy access from one level of abstraction to another.

Research conducted by science educators provides descriptions of the organization and representations of mechanics knowledge (motion-of-objects schemata) in uninstructed students. Motion-of-objects schemata of uninstructed students are situation-specific, thus suggesting that no naive abstract representation is extant in the schemata to make them appear to be applicable to a large number of physical situations (Gunstone, 1980).

This last characteristic was exemplified in our work with middle-school students (Champagne, Klopfer, Soloman, & Cahn, 1980). We have observed that, given four physical situations, all of which could be explained by using Newton's Second Law ($F = ma$), students never give any indication that they perceive that a common explanatory system might be applied to all four of the situations. In fact, they never notice that a proposition they have used to explain the motion in one of the situations is directly contradicted by a proposition they use to explain the motion in another situation. This failure to see the contradiction suggests that they are unaware of any need for consistency across situations. For example, students do not recognize that the same physical laws apply to objects in free fall and to objects sliding down an inclined plane. At one point during a class discussion, for example, students agreed that two carts of unequal mass, but equal volume, would strike the ground at approximately the same time when dropped from the same height. When they were asked to compare the times for the carts to slide down an incline, however, only one of them argued that the times would be about the same.

Problem solving strategies of experts and novices. Cognitive research on problem solving has generated detailed specifications of

problem solving strategies for many categories of problems (Greeno, 1978; Newell & Simon, 1972; Larkin, Note 1). One finding from this research that is particularly pertinent to the instruction we propose is reported by Larkin. Her analyses of thinking-aloud protocols indicate that expert physicists perform a preliminary qualitative analysis before proposing equations for the quantitative solution of the problem. In contrast, novices immediately begin the search for an equation and proceed to match the information presented in the problem with terms in the equation.

Given that the beginning students' explanatory schemata are so situation-specific, it is hardly surprising that their problem solving strategy is similarly bound to the perceived situations. The students' main strategy for solving motion-of-objects problems is to try to recall a rule or relationship which they believe to be applicable to the specific situation at hand. Rarely, if ever, is there any evidence that the beginning students are aware of general problem solving strategies, related to general physical principles or laws, which are applicable across many situations.

Differences in Structure and their Instructional Implications

Empirically-derived descriptions of the characteristics of the schemata of uninstructed students, novices, and experts are summarized in Table 1. This summary makes evident the contrasts and similarities in the characteristics of the three groups' schemata with respect to principles, surface features, and second-order features, each of which is briefly explained in the first column. Also summarized in Table 1 are descriptions of the problem solving strategies for each group.

Precise descriptions of the differences in the organization and representation of the physics knowledge of individuals at different levels of competence provide a further basis for the specification of the goal and objectives for beginning mechanics instruction and allow us to generate hypotheses about (a) how current instructional practice may impede the attainment of the goal and (b) alternative instructional mechanisms that will facilitate the attainment of the objectives.

Contrasting the problem solving strategies and organization of the mechanics knowledge of experts, novices and uninstructed students yields the following goal for beginning mechanics instruction: Development of a well integrated motion-of-objects schema that is organized in a way that produces (a) the solution of mechanics problems via the method of qualitative analysis and (b) the analysis of the motion of objects in the real world using the tenets of Newtonian mechanics. The detailed specifications of the mechanics knowledge organization to be accomplished as the result of instruction constitute the instructional objectives subsumed under the goal.

Empirical evidence demonstrates that current instructional practice does not facilitate the attainment of identified goal. Students generally do not learn to relate their mechanics knowledge to real situations as the result of either high school or beginning college physics instruction. Based on a cursory analysis of physics texts and our knowledge of physics instruction, we conclude that preliminary qualitative analysis of physics problems is seldom if ever taught explicitly. In fact, problem solving instruction in physics textbooks makes no attempt to link the physical features of the real-world situations described in physics to the abstract concepts and principles of the Newtonian framework.

Physics texts teach the problem solution strategy that novices typically use. The first step in sample solutions is the presentation of the equation that will yield a quantitative solution to the problem. There is no attempt to instruct the student in the expert physicists' analytic procedures which result in abstract representations of physical situations in terms of abstract concepts. These concepts are vital because they in turn can be linked to principles or laws of mechanics and formal expressions of the principle or law (formulas) which can then be applied to reach a quantitative solution of the problem.

The traditional practice is counterproductive in two respects: (a) It teaches a problem solution strategy that does not approximate the strategy exemplified by the ideal state, and (b) It does not encourage the development of links in cognitive structure between real-world situations and the abstract representations of physical situations that characterize the to-be-approximated schemata.

Experiences contributing to the expert's cognitive state. An interesting theoretical question, with implications for both practice and theory, should now be posed: In the absence of direct instruction, how do experts come to develop the qualitative analysis strategy and the conceptual links between physical situations and the appropriate abstract representations?

Table 1
Problem Solving Strategies and Schemata of Uninstructed Students, Novices, and Experts

PROBLEM SOLVING STRATEGIES

UNINSTRUCTED STUDENTS	The typical procedure for solving problems is to find a general rule which appears to cover the physical situation described in the problem, and then to use the relationship described in the identified rule deductively to derive an answer to the problem. Rules to be employed in this process may be recalled from experiences with similar physical situations, or they may be recollections of authoritative statements from books or people.
NOVICES	The principal procedure for solving problems is to instantiate variables in equations. This procedure may be chained through a series of equations. Abstracted solution methods are lacking.
EXPERTS	Associated with the organizing schema are its specific conditions of applicability and the necessary problem solution methods. Experts abstract a basic solution strategy from the surface features of the problem and engage in qualitative analysis of the problem prior to determining a quantitative solution.

SCHEMATA

FEATURES OF SCHEMATA	CHARACTERISTICS OF UNINSTRUCTED STUDENTS' SCHEMATA	CHARACTERISTICS OF NOVICES' SCHEMATA	CHARACTERISTICS OF EXPERTS' SCHEMATA
PRINCIPLES Ideas of some degree of generality that express relationships; principles are applied to solving problems; can serve to organize schemata.	Principles are generalized rules derived from everyday experiences (world knowledge). They are imprecise propositions. The imprecision is due to vagueness about the meaning of concepts, errors of scale, and inappropriate formulations of general rules. The principles (rules) have limited scope and tend to be situation-specific. The notion that an abstract principle can apply to a range of different physical situations is lacking or poorly developed. There appears to be no awareness of the need for consistency along the rules that cover different physical situations.	Principles are relationships between physical variables expressed as equations or rules. Some of the principles are the major physical laws expressed in equation form, but there is no evidence that they serve as organizers of schemata.	Principles are major physical laws, which are highly abstract and express relationships of great generality. Included with each principle are the conditions under which the principle applies. Each principle has an associated schema, which is oriented by the content and applicability conditions of the principle. The applicability conditions usually are expressed in terms of second-order features.

OBJECTS AND PHYSICAL CONDITIONS (SURFACE FEATURES) Physical objects and conditions described or presented in a problem situation; physical features of objects and their states of motion or position that are directly perceivable from verbal description; diagrams or direct observation of the physical situation.	Concrete objects and the directly observable properties of objects are present. A reasonable inference is that the objects and properties define the specific physical situation which, in turn, directs the search in memory for a general rule that covers it.	Physical objects and their surface features are the basis for categorizing problems. It is inferred that an object or a configuration of objects functions as the organizing element (node) in its schema for the problem. The content of the representations may be concrete objects or abstractions at the level of diagrams.	Concrete objects, their physical configurations, and diagrams of objects are present in the schemata, but none of these is prominent. It is inferred that objects serve primarily as vehicles for identifying second-order features, and that sometimes they trigger the activation of a particular principle-based schema.
PHYSICS CONCEPTS AND SYMBOLS (SECOND-ORDER FEATURES) Idealizations of physical objects (e.g., an elephant is represented as a point mass), and constructs or entities (e.g., energy, force); conventional representations of physical entities (e.g., vector components).	There is no evidence that second-order features are represented in these schemata. Concepts and terms are present, but many are poorly differentiated. The meanings of the terms are their real-world meanings, rather than their technical meanings in physics.	Some conventional representations of physical entities are present, and idealizations of physical objects may be used in problem representations. Concepts and terms related to the objects which dominate the problem-solution schema are present. Novices report taking terms directly from the problem statement to identify equations that could be approximately employed in solving the problem.	Representations of physical objects in their idealized form are prominent, with the content of the representations determined by the organizing schema. Physical entities are represented according to the conventions of the field. Features abstracted from the problem statement are also present. Some experts report that these features help to select the basic approach to problem solutions, thus indicating direct links between these second order features and principles. Concepts relevant to the organizing schema are present. Associated with each concept are its interconnections of relations with other concepts and with the schema's major physical law.

For the purpose of our discussion, we consider three factors that differentiate the experiences of experts from the experiences of novices; these are: (a) additional formal instruction, (b) more extensive practice in solving problems, and (c) more extensive verbal interactions about physics. The Chi et al. (1981) study suggests that the contents of novices' data structures for particular types of physics problems are similar to those of experts with respect to objects, concepts, and terms; however, experts' data structures contain many more linkages. The more extensive data base, which experts acquire as a result of their greater exposure to formal instruction, is not necessary for the successful solution of probblems of the type on which the analysis of expert-novice differences is based. However, the additional links in experts' knowledge structures are necessary for the successful and efficient solution of mechanics problems.

We hypothesize that these links develop as a result of extensive practice in problem solving and that their development is facilitated by verbal interactions. The professional activities of physics experts require either verbal interactions with others or the organization of physics information for the purpose of communicating it to others. We hypothesize that this type of experience is important to schema change because the individual must make explicit the meaning attributed to technical terminology and the rules for applications of proposition and principles.

This analysis leads us to hypothesize that providing beginning students with opportunities to engage in the quantitative analysis of physics problems will facilitate the development of physics knowledge organized in ways that approximate that of the organization of a physics expert. Our selection of this instructional strategy to attain this goal is based on the recognition that: (a) The cognitive objectives of beginning mechanics instruction should approximate the skills and knowledge applied by experts in the solution of mechanics problems; (b) Explicit instruction in the knowledge and skills required for successful novice performance is not now a part of physics instruction; and (c) Part of such instruction must focus on producing a schema change in students which results in the incorporation and integration of mechanics principles and interpretations of real-world phenomena.

We hypothesize that providing learners with opportunities for verbal interactions will facilitate the development of correct usage of technical vocabulary and help students become aware of the principles they apply in the analysis of physical situations and how their principles are different from those being taught. This hypothesis is consistent with cognitive theory of schema change.

Schema change theory. The processes by which existing schemata are modified are just beginning to be understood (Greeno, 1980). Information processing models of schema development generally have not gone beyond the level of describing stages. Nonetheless, several valuable ideas concerning the development of schemata and suggestions for modifying schemata have been offered.

Two principal mechanisms for schema modification have been discussed by Rumelhart and Ortony (1977). Each mechanism is, in a sense, the antithesis of the other. Specialization occurs in a schema when one or more of its variables are fixed to form a less abstract schema. Conversely, generalization occurs in a schema when some fixed portion is replaced by a variable to form a more abstract schema. The generalization mechanism can be applied in a motion-of-objects schema.

The typical uninstructed student has the motion schema: *A push produces motion.* As a result of appropriate instructional experiences, the student's motion schema could become: *A force produces acceleration.* The fixed portion, *push*, in the initial schema has been replaced by a more general variable, *force*, which can take on several values in addition to *push*. Similarly, the general variable, *acceleration*, which can have different values, has replaced the initial schema's fixed portion, *motion*. The modified schema is considerably more abstract and, hence, should have a much broader range of applicability.

The hypothesized generalization mechanism only describes the changes and is, in fact, not a mechanism for producing them. If, as Rumelhart and Ortony (1977) imply, the generalization mechanism is a mechanism for producing change, a reasonable implication is that the modification of the motion-of-objects schema might be accomplished quite simply by describing to students the needed modifications in definitions of terms and restating simple propositions. Empirical evidence on mechanics learning demonstrates that this instructional strategy is not generally effective

and suggests that, while the gradual modification of schemata doubtlessly involves generalization and specialization, in highly integrated schemata more dramatic changes, amounting essentially to a shift to a new paradigm (in Kuhn's [1962] sense), must also take place.

To bring about schema change on such a large scale, a dialectical process appears to be necessary. Riegel (1973) points out that the thinking of both adults and children is dialectical, and he proposes that dialectics is "the transformational key" in cognitive development. Anderson (1977) suggests that ". . . the likelihood of schema change is maximized when a person recognizes a difficulty in his current position and comes to see that the difficulty can be handled within a different schema (p. 427)."

As the mechanism for promoting dialectics in the classroom, Anderson advocates the use of a Socratic teaching method. By participating in the dialogues which occur in Socratic teaching, the student is forced to deal with counterexamples to proposals and to face contradictions in his or her ideas. To overcome the attacks of adversaries in the dialogues, the student must construct a new framework of ideas that will stand up to criticism. The newly constructed framework is, of course, a new schema, so it may be said that schema change has occurred as a result of the student's participation in the dialogues.

Instructional Issues

Specification of Instructional Objectives and Strategies on the Basis of Cognitive Analysis

Table 2 summarizes instructional objectives and strategies for mechanics instruction derived from the analysis of the cognitive states of uninstructed students, novices, and experts, groups who differ with respect to (a) the quantity and extent of formal mechanics instruction, (b) experience in solving mechanics problems, and (c) the extent of their verbal interactions about mechanics.

Objectives. The objectives presented in Table 2 are based on the analysis of contrasting cognitive states and represent the first in a series of steps in the detailed specification of instructional objectives. These objectives specify features of the ideal state which the learner will approximate but do not detail how far the learner will move along the continuum from beginning student to expert as the result of a particular course or sequence of instruction. Further refinement of the objectives for a certain instructional sequence must take into account many other factors, including the content the instruction will cover, the time available for instruction, and the age and academic aptitude of the students for whom the instruction is intended. However, the analysis here illustrates one important principle employed in the cognitive approach to design. That principle is the comparison of the cognitive states of individuals at different levels of competence (Greeno, 1976). Furthermore, the design requires that the initial specification of objectives be based on the cognitive features that distinguish the learner for whom the instruction is designed from individuals competent in the field.

An observation worthy of comment is the difference between these objectives based on cognitive analysis and objectives that derive from the logical analysis of the subject matter or from the identification of to-be-learned behaviors. Objectives derived from these two processes are deficient in at least two respects. First, cognitive analysis identifies significant objectives not identified by either analysis of behaviors or logical analysis. Second, logical analysis does not identify the structural organization of knowledge which the instruction should produce. For example, logical analysis would not identify qualitative analysis of physics problems as an objective of instruction, nor would it produce information about the optimal structural organization of mechanics knowledge for competent problem solving.

Instructional strategies. The first approximation of instructional objectives derives from the comparison of the cognitive states of uninstructed students and experts. Possible instructional strategies for the attainment of the objectives derive from comparisons of the cognitive states of uninstructed students, novices, and experts, and from examinations of the mechanics-relevant experiences of novices and experts. Having specified the differences in cognitive states and relevant experiences we can generate hypotheses for explaining the observed differences in cognitive states on the basis of differences in experiences. These hypotheses, in turn, suggest possible instructional strategies.

Table 2
Contrasting Features in Cognitive States and Their Related Instructional Objectives and Strategies

Contrasting Features in Cognitive States of Uninstructed Students (U), Novices (N), and Experts (E)	Instructional Objectives Derived from the Contrasts	Instructional Strategies to Facilitate Attainment of Instructional Objectives
CONCEPT MEANING Meanings attributed to technical terms by U differ in significant ways from the meanings of E and N. Example: U - acceleration means speeding up; E and N - acceleration means a change in the magnitude or direction of velocity.	Students know both the everyday meaning and the canonical definition of mechanics and can specify differences between the everyday and canonical meanings.	*Interactive dialogue:* Provides students with opportunities to become aware of the meanings they attribute to physical concepts, how these meanings differ from context to context. Examples: (1) doing physics problems or describing a physical event to a friend, or (2) doing mechanics problems in which there is no motion. Dialogue provides students with opportunities to contrast their meanings of concepts with those of the physicists.
CONCEPT DIFFERENTIATION U do not differentiate mechanics concepts. Example: U - *weight* and *mass* are the same thing; N and E - *mass* and *weight* are perfectly correlated but distinct.	In analyzing a given physical situation, students can explain which of two poorly differentiated concepts is the relevant concept to apply.	*Interactive dialogue:* Provides students with opportunities to verbalize their analysis of physical situations in a way that simply substituting 9 g for mass (m) or 45 dynes for weight (F) in an equation does not. We hypothesize that the verbalization will help differentiate weight (a force) expressed in dynes from mass expressed in grams. [Also see strategy on Structural Features row below.]

PROPOSITIONS IN SCHEMATA U - presence in schema of incorrect propositions. Example: motion implies force. N - presence in schema of conflicting propositions which are applied in different situations. Example: Motion implies force proposition applied in the analysis of real-world situations. Change in motion implies force proposition applied in the quantitative solution of physics problems. E - propositions present in schema are internally consistent and widely applicable. Example: Change of motion implies force proposition is applied in analyzing all pertinent problems.	Students apply change in motion implies force proposition in real-world situations. Students contrast implications of the difference in the two relationships between force and motion expressed by the propositions (1) Motion implies force, and (2) Change in motion implies force.	*Instructional dialogue to change contents of mechanics schema:* Provides opportunity for students to (1) be explicit about the propositions they assume in invoking the presence of forces in physical situation (For example, U generally invokes forces only in situations where there is motion.) and (2) make explicit the relationship between motion and force in the propositions they use.
STRUCTURAL FEATURES Concept integration of U and N is sparse, with fewer links among concepts than for E. Example: N - experientially derived motion-of-objects schema is not integrated, or reconciled with Newtonian mechanics schema. Integration of representations in U and N is poor, while they are well-integrated in E. Example: N - representations of surface features of physical situations are poorly integrated with abstract representations of physical situations; these, in turn, are poorly integrated with propositions which link canonical objects and physical constructs used in abstract representations; E - representations of surface features of physical situations are integrated both with abstract representations of physical situations and with propositions linking the canonical objects and constructs of abstract representations.	Students qualitatively analyze mechanics problems: (1) Produce an abstract representation of a physical situation. (2) Recognize that situations with very different surface features can have the same abstract representation. (For an example, see Appendix A where the situations of 6 problems have the same abstract representation.) (3) Recognize that the problems can be solved by the application of the same mechanics principle.	*Qualitative analysis of problems to change structural features of mechanics schema:* Forges links between the physical situation, its abstract representation using canonical objects and mechanics constructs, and the principles (Newton's second law, F = ma) which link properties of the canonical objects and constructs. Also forges links between concepts (e.g., between *mass* and *weight*) to integrate them better, thereby contributing to concept differentiation.

Table 2 (continued on next page)

Table 2 (continued)

PROBLEM SOLUTION STRATEGY U solution strategy: search for a rule that applies to the given situation. Example: Problem of comparing speeds of two falling objects evokes the rule - Heavy objects fall faster than lighter objects. N solution strategy: search for an equation E solution strategy: qualitative analysis	Students engage in qualitiative analysis of physics problems before attempting quantitative solutions.	*Interactive dialogue*: Demonstrates that the same abstract representations and diagrams derive from problems with different surface features. Also demonstrates the usefulness of a general principle for solving a large number of problems with different surface features. *Qualitative analysis of mechanics problems*: Provides practice in using the desired strategy.

The potential for effectiveness of alternative instructional strategies is then evaluated in terms of relevant psychological theory.

The availability of empirical descriptions of differences between uninstructed students and novices is particularly important to the process of selecting instructional strategies. Information about these differences leads to the identification of instructional strategies which are effective and those which are not effective or counterproductive. The observation that novices' cognitive contents resemble those of experts is an indication that the didactic method of instruction is effective for imparting discrete bits of information. However, the detailed analysis of problem-solving behaviors of novices suggests that their structural organization of information resulting from exposure to didactic instruction is less than satisfactory.

In the case of mechanics, this analysis also reveals that the problem-solving strategy taught in physics textbooks is indeed demonstrated by novices, but, as we discussed earlier, this strategy does not produce certain desired links in cognitive structure, specifically those between physical situations and mechanics concepts. This lack of structural integration is also evidenced by the fact that many novices continue to apply non-Newtonian principles when asked to analyze real-world situations.

The analysis of novice-expert differences is a useful source of possible alternative instructional strategies. For example, the proposed influence of problem-solving and verbal interaction in the development of correct and well-integrated cognitive structures are derived directly from cognitive difference analysis. This interpretation of the differences is consistent with cognitive theory and with educational practice and philosophy. The cognitive analysis provides an explicit causal link between the strategy and the outcomes, thus making possible more convincing empirical tests of the effectiveness of the strategy. Our assertion — that engaging in qualitative analysis of mechanics problems will develop a better integration of real-world situations and their abstract representation utilizing the concepts and symbols of Newtonian physics — is empirically testable.

Procedural Description of the Proposed Instruction

Although the strategy of using dialogues in instruction has been specified in relation to the attainment of instructional objectives (Table 2), we have not yet described how this strategy is implemented. Illustrative procedures which employ the strategy are outlined in this section. In one mode of the dialogues strategy, students engage in interactive dialogues with each other.

First the students are presented with a set of mechanics problems which require qualitative answers. A typical set of six such problems is shown at the right side of Appendix A. These problems are qualitative restatements of problems from five different physics textbooks. The physical situations or surface features of these problems (in both the qualitative and quantitative versions) are very different, but all problems can be represented in the same abstract form (diagram or verbal description using mechanics concepts) and can be solved using the same mechanics principle. Each student produces a solution to each of the problems and then shares with the class the problem analysis, the solution of the problem, and definitions of technical terms used in the solution or the analysis. This procedure forces students to be explicit about the idiosyncratic meanings attributed to technical terms and the principles and propositions that they apply in the analysis of the problem. Each student can contrast his or her solution strategy for a problem with the strategies presented by other students.

When all of the problems in the set have been considered by the class, the teacher will present the physicists' analysis of the problem by means of diagrams and verbal explanations using the technical vocabulary of mechanics. The expert analysis is based on the common deep structure of the six problems, as shown in Appendix A. The teacher will demonstrate that the abstract representation is the same for each of the problems and that the same principle will produce a solution to all the problems in the set. Then students will analyze their solutions to the problems in light of the physicists' solution and will specify how their interpretations differ from that of the physicists.

The teacher's presentation of the physicists' analysis and solution of qualitative problems is in the mode of an instructional dialogue. In order to explain and illustrate this mode of the dialogues strategy, we have analyzed physics problems from introductory texts in the manner shown in Appendix B. The general structure of the analysis is simple. Initially the

textbook problem was rewritten as a qualitative problem and subsidiary questions were added asking about the assumptions and physics principles used in obtaining the answer to the problem. Then a realistic minimum state in terms of relevant prior knowledge and experience was selected, and a strategy for working from that state to a successful solution was worked out. At this stage, when we do not have the insights to be derived from data, it is assumed that other, more developed responses can be accommodated by beginning at a later point in this sample strategy.

The strategy has been outlined only. It indicates a series of logical steps. Within each step, the essential concept(s) to be developed and the purpose of the step in terms of the problem solution are indicated. In some cases a particular instructional methodology to be used for a step is shown, while in the remaining cases only instructional dialogue is anticipated. For each the rationale for the procedure is described, referring to the techniques identified by Collins (1977) and Collins and Stevens (1981) when appropriate. A strategy for handling a correct answer to the questions asked so as to develop a solution strategy for the problem is also given.

Concluding Remarks

In this article we have recounted how our interest in a particular instructional problem in introductory physics, students' difficulty in learning mechanics, provided the occasion for utilizing Simon's characterization of a science of design as a guide in proceeding to design an instructional strategy that can be used to help students learn mechanics effectively. We have shown how the theory and empirical findings of cognitive science and the cognitive psychologist's analytical tools and procedures were brought to bear on every stage of the design process. We have sought to make explicit the particular principles of instructional design which both evolved and were applied in the course of the inquiry. We suspect that these instructional design principles may be applied in various school subject-matter domains, though only their application in physics was illustrated here.

The instructional strategy for guiding uninstructed physics students in their learning of Newtonian mechanics is now available, but our inquiry is not at an end. We are now preparing to investigate empirically several issues which were raised during the process of designing the instructional strategy. The major hypothesis to be tested in our proposed research is that engaging uninstructed physics students in instructional dialogues focused on the qualitative analysis of mechanics problems will produce changes in the students' motion-of-objects schemata. A further hypothesis is that, after completion of the specified instruction, the students' cognitive state will approximate significant features which are characteristic of the cognitive state of a physics expert.

We can admire the great psychologists of earlier days, such as Charles H. Judd, whom we quoted at the start of the paper, for their keen perspective on students' learning of abstruse school subjects like physics. Judd's insight (or perhaps, intuition) seems so right and true that we cannot help being amazed. Also amazing is the realization that the situation which Judd described seven decades ago still rings true for physics textbooks and physics learning today. Hardly anything seems to have changed in the interim. Why is this so?

The main reason, we believe, is that, although Judd recognized the problem, he could not prescribe an effective solution. Because he was unable to describe the problem precisely, Judd had no basis on which to evaluate the probability of the effectiveness of possible instructional strategies. Today the status is different. Empirical and theoretical research in cognitive psychology make possible the construction of theoretical models, on which predictions can be based. The application of a model of understanding of physical phenomena leads to detailed specification of a strategy for beginning physics instruction which can be expected to produce desired changes in students. The difference between our present possibilities and those of Judd's day is demonstrated in this article.

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Appendix A

Six Physics Problems with Different Surface Features and the Same Deep Structure

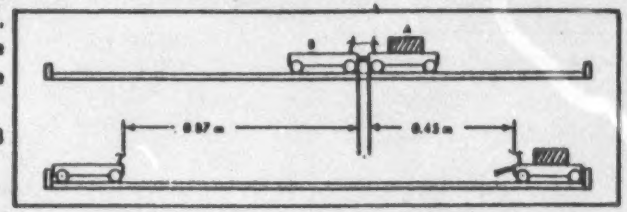
QUANTITATIVE VERSION	QUALITATIVE VERSION
1. Boy and Wagon Problem A boy of mass 20 kg is standing in a wagon of mass 10kg. The boy jumps off to the right with a speed of 20 m/sc. What happens to the wagon? (Ignore friction.) (Hulsizer & Lazarus, 1972, p. 187)	A boy is standing in a wagon. The boy jumps off one end of the wagon. Ignoring friction, describe the motion of the wagon. How does the velocity of the wagon compare with the velocity of the boy?
2. Boy and Raft Problem A 50 kilogram boy is standing on a 500 kilogram raft floating on a lake. The raft is at rest. It can move on the surface of the lake with negligible friction. Starting from rest, the boy begins to walk with constant speed 1 meter/sec (relative to ground) and continues to walk for 20 seconds. How far does the raft move in this time? (Smith & Cooper, 1979, p. 152)	A boy is standing on a floating raft on a lake. The raft is at rest. It can move on the surface of the lake with negligible friction. Standing from rest, the boy begins to walk with constant speed towards the shore. Describe the motion of the raft. How does the speed and direction of motion of the raft compare with the speed and direction of the boy?
3. Rifle and Bullet Problem A 3-g bullet is fired from a 2.4-kg rifle with a velocity of 360 m/s north. Find the momentum of the bullet and the recoil velocity of the rifle, assuming that no other bodies are involved. (Smith & Cooper, 1979, p. 93)	A bullet is fired from a rifle. Describe the motion of the rifle. How does the velocity of the rifle compare with the velocity of the bullet?
4. Skaters Problem Two skaters are stationary in the center of a circular rink. They then push on one another so that they fly apart. One of the skaters has a mass of 90 kg and acquires an initial velocity of 0.8 m. sec. If the other skater has a mass of 75 kg, what is his initial velocity? (Atkins, 1965. p. 119)	Two skaters are stationary in the center of a circular rink. The skaters push on each other. Describe the motion of each skater. How do their velocities compare?

5. Carts and Spring Problem

Two heavy frictionless carts are at rest. They are held together by a loop of string. A light spring is compressed between them (see drawing). When the string is burned, the spring expands from 2.0 cm to 3.0 cm, and the carts move apart. Both hit the bumpers fixed to the table at the same instant, but cart A moved 0.45 meter while cart B moved 0.87 meter. What is the ratio of:

(a) The speed of A to that of B after the interaction?

(b) their masses?

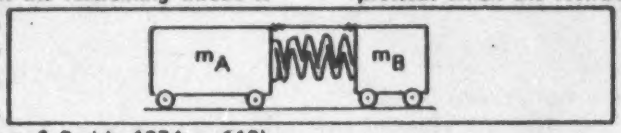


(Haber-Schaim et al., 1976, p. 321)

Two heavy frictionless carts are at rest. They are held together by a loop of string. A light spring is compressed between them. The string is burned and the spring expands. Describe the motion of the carts. How does the velocity of cart A compare with the velocity of cart B?

6. Compressed Spring Problem

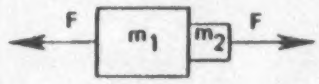
Two objects of mass m_A and m_B are held together by a strong light thread, and are also acted on by a light spring that is compressed as shown in the figure. When the restraining thread is broken, the two objects fly apart with velocities $-v_A$ and $+v_B$. Use the law of conservation of momentum to solve for the ratio of the velocities, v_A/v_B.



(Miller, Dillon, & Smith, 1974, p. 112)

Two objects of mass m_A and m_B are held together by a strong light thread, and are also acted on by a light spring that is compressed. When the restraining thread is borken, the two objects fly apart with velocities $-v_A$ and $+v_B$. Use the law of conservation of momentum to solve for the ratio of the velocities, v_A/v_B.

PHYSICIST'S ANALYSIS



Forces of equal magnitude and opposite in direction are exerted on two unequal masses at rest. How do the velocities of the masses compare? How do the displacements of the masses compare?

Appendix B

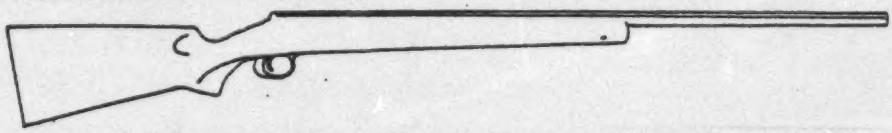
Example of Proposed Instructional Dialogue – The Gun and Bullet Problem

Original Problem

"1. A gun has a mass of 2.00 kg. It fires a bullet of mass 0.005 kg towards the right with a speed of 500 m/sec. How does the gun recoil? (Give its speed and direction of motion.)"

(Hulsizer & Lazarus, 1972, p. 187)

Problem Restated in Qualitative Form



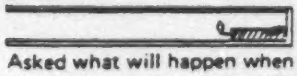
When a gun is fired, the bullet leaves the gun with some speed. How does the bullet's speed at the muzzle of the gun compare with the gun's speed at that time? How does the direction of the bullet's motion compare with the direction of the gun's motion?

Subsidiary questions: (i) What assumptions did you make to arrive at your answers?
(ii) What principles of physics/laws of motion did you apply to the situation in coming to your answers?

Knowledge/skills assumed in following outlines of Instructional Dialogue strategies:

1. "Physics" knowledge: it is assumed that students have completed a study of kinematics.
2. General (or "world") knowledge: Awareness of medieval cannons, rifles, handguns (see step A1 below).

Strategy A Outline of strategy to be used for responses to the qualitative problem of the form "don't know" or "gun doesn't move."

Steps in the Strategy	Purpose of Steps	Commentary on Steps
A1(a). Given *scale* drawings of a small pistol, rifle, small mortar, medieval cannon and shells/bullets fired by each, student is asked to match the guns and shells/bullets.	A1(a) and (b). To establish that, in the real world, mass/weight of gun > mass/weight of bullet or shell.	Collins (1977) has proposed a series of production rules for this form of instructional dialogue. Strategy A1(a) is an example of Rule 1: Ask about a known case. In his subsequent reorganization of these rules (Collins & Stevens, 1981), this is an example of Case Selection Strategy 1: Pick a positive exemplar for a set of factors.
A1(b). Ask student why matchings were made.		Collins (1977) Rule 2: Ask for any factors.[a]
A2. Ask the student why the bullet/shell comes out of the gun when the gun is fired.	To establish the role of explosion in this phenomenon. If this notion is present, go to A4; if not, go to A3.	Collins (1977) Rule 2 (see above).
A3. Show the student a drawing of a metal tube, closed at one end and with a lighted fire cracker placed on it.  Asked what will happen when the fire cracker goes off.	To establish the effect of explosion on the mass in the tube, i.e., the cracker. If this exercise does not establish the notion, move further to considering a medieval cannon where the explosive and propelled object are separate.	Collins (1977) Rule 3: Ask for intermediate factors. For some students this will also be a prompt to recall a relevant previous experience, relevant existing world knowledge.

Appendix B (continued)

Steps in the Strategy	Purpose of Steps	Commentary on Steps
A4. Using two laboratory trolleys, one containing a spring plunger (PSSC), and a number of bricks.[b]		
(a) have students experiment qualitatively with the effect of placing two carts with loaded spring between and releasing the spring, with varying masses on the carts,	To establish the separation of all masses involved in an explosion; to establish that smaller mass pieces move more quickly than larger mass pieces.[c]	Direct observation
(b) have students experiment with one cart carrying various masses placed with loaded spring against their hand and then released.	To establish that a mass exploded away from a "rigid" body results in a force on that rigid body.	Direct observation
A5. By drawing on A1-A4, assist the student to establish (and, if appropriate, to link to relevant existing knowledge/experience): (i) that in the case of the exploding carts, the expanding spring exerts forces on the carts placed at either end of the spring, and that these two forces are equal in magnitude. (ii) that, in the case of the exploding carts, equal forces from the spring acting on carts of different mass result in different cart velocities after explosion. (iii) that, in the case of exploding carts, when one cart has a mass considerably larger than the other this situation is in some ways analogous to a gun firing a bullet. (Of the limitations to the analogy, the most important to be drawn out here is that the relative mass differences for gun and bullet are much greater than for the carts.)	To establish the generalizations needed in order to be able to analyze and solve the original qualitative problem.	This step is similar to Step A1 (b) (see Footnote a) in that the production rules to be applied will vary from subject to subject, depending both on each individual's existing knowledge and beliefs, and on each individual's interpretations of steps A1 to A4.
A6. Return to qualitative problem. After successful solution of the problem as asked, use strategy B below if appropriate.		

Appendix B (continued)

Strategy B Outline of strategy to be used for responses to the qualitative problem of the form "speed of bullet very much greater than speed of gun and in opposite direction" (i.e., correct answer to questions asked).

Steps in the Strategy	Purpose of Steps	Commentary on Steps
B1 Ask student if they can be more precise about the relative values of the bullet and gun speeds.	To establish that the ratio of speeds is the inverse ratio of the weights/masses involved. If this is not forthcoming, go to strategy A, beginning at A4. If some such statement is produced, go to B2.	Collins (1977) Rule 4: Ask for prior factors.
B2 Repeat subsidiary questions (i) and (ii) from the qualitative problem.	To elicit a statement of Newton's Third Law and to have the student authoritatively link this law to the gun/bullet phenomenon.	See commentary on Step A5.

[a] Numbers of other rules (e.g., Rules 3-11) may be applied in the exploration of individual responses. For example, it may be necessary to ask "Could the cannon ball be fired from the pistol?" (Rule 6: Pick a counter example for an insufficient factor.)

[b] Previous experience suggests that a physical mark (e.g., a chalk line) needs to be made to indicate the position of carts before the explosion so that a reference is available for considering post-explosion effects.

[c] If friction effects provide an interfering concept, move further by using an air track for explosions and then returning to trolleys.